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Fault-Tolerant Valve Control

Abstract: Valves have a key position in safe, reliable, and economical operation of process industry plants. Valves consist of moving parts subject to wear and dirt. During a fault, it is important that the valve controller eagerly tries to keep the valve under control, despite of changes in the operating environment. In this paper we discuss valve faults on a general level, and we present a solution for keeping valve under control despite of a missing valve position measurement. Our solution utilizes valve/actuator models and real-time simulations to generate a virtual valve position sensor. When valve position measurement is lost, the controller will continue as before, but the real position measurement is replaced with a soft sensor value.

Keywords: industry, valve, valve controller, fault-tolerant control

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1 Introduction

Process industry plants, such as oil refineries, pulp mills and chemical production plants, are highly automatized. The automatic operation is based on a network of sensors, controllers, and actuators.

The most common actuators are the valves, which are used to control liquid and gas flows in pipelines. An industrial valve consists of three parts: 1) a valve body, attached to the pipeline, 2) a pneumatically powered actuator, and 3) a valve controller, which controls the valve position according to the setpoint obtained from the process automation system [1]. Today's valve controllers are intelligent digital devices with various features that supports plant operation during its entire life time.

The valves have a key position with respect to safe and reliable operation of the plant. It is important that all devices contribute to safe and controlled responses during a failure. A wide range of options must be supported: from continued operations (with some reduced performance) to a safe and controlled shut down.

Some valves may have a critical position regarding plant operation, i.e. if a valve fails, a part of, or the entire plant must be shut down. Therefore, a valve controller should eagerly fight against faults and try to keep valve under control despite of minor faults. A difficult case is loss of valve position measurement. In this paper we discuss some safety and fault-tolerant features of the Neles NDX valve controller, and we present a method for keeping control over the valve in case of a faulty valve position sensor.

2 Valve controller basics

A valve controller has two main tasks. First it receives a valve position setpoint, typically from a process automation system, and secondly, it controls the valve position according to the setpoint.

A typical valve controller is illustrated in Figure 1. The main components include a PCB with integrated sensors, a Prestage unit (an I/P converter), and an Output Stage (a pneumatic relay).

A local user interface enables easy commissioning and a possibility for manual operation and parameter changes. The milliampere signal powers the device and provides analog setpoint and standardized HART digital communication. A set of sensors provide necessary measurements needed for valve control, and a position transmitter enables an analog valve opening signal.

The microprocessor compares valve position measurement to its setpoint and generates an electrical signal to the Prestage. The Prestage pressure actuates the Output stage, which controls air flow into or out of the actuator. The valve controller keeps adjusting the Prestage signal until the valve reaches its desired position [2].

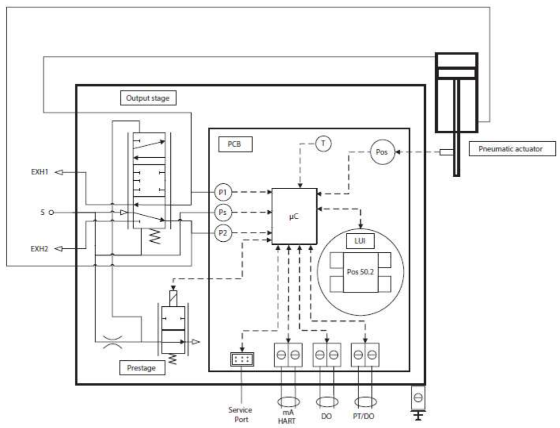

Figure 1. Operating principle of a valve controller.

Valve controllers have traditionally employed some feedback control algorithm for controlling the valve position. If actuator pressure measurements are available, some cascade control structure can be used to speed up valve control. An example cascade control structure is illustrated in Figure 2.

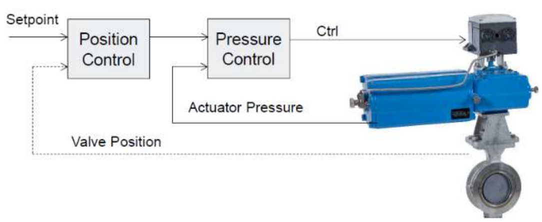

Figure 2. A typical valve control structure based on valve position and actuator pressure measurements.

3 Valve Faults

Various faults may occur during valve operation. We can divide faults into two categories: faults that imply loss of controllability and faults with retained controllability. If we lose valve controllability, e.g. during loss of pneumatic pressure or electrical power, then valve moves to a pre-determined fail-safe position.

If controllability of valve is retained, we can further divide the faults into two categories: 1) mechanical faults and 2) sensor faults. Typically, mechanical faults affect control performance but does not necessarily imply a need for urgent replacement of faulty valve package part. However, depending on the fault and its severity, we typically get some increased position control error or valve hunting as a result.

The most critical sensor for valve control is the valve position sensor. For any other sensor fault, we can switch to simple position feedback control during a fault.

The Neles NDX valve controller position measurement is based on a magnet sensor. This solution has many advantages as it enables accurate position sensing without mechanical links in harsh conditions. However, if the magnet is significantly moved away from its original position or if the positioner or its bracket is moved, tilted, or rotated, it may affect sensor reliability. Therefore, situations may occur where NDX cannot access the position measurement. To prevent an unplanned shutdown because of missing valve position readings, we have developed a method for valve position control without position measurement.

4 Fault-tolerant control

With fault tolerant control we mean the ability of a controller to retain controllability despite of faults in the control network. Usually we tolerate some reduction in the control performance, but the main goal is to continue running the process despite of the fault.

For valves, fault-tolerant control due to mechanical faults and sensor faults are discussed next.

Mechanical faults

Typical problems in valve control include air leakage in pneumatic actuator, increased friction in valve body, freezing, and valve controller faults (e.g. defectives in pneumatic components). These faults may affect valve control accuracy, but normally we can continue operation without a need for replacement of devices or spare parts.

For mechanical faults, fault-tolerant control typically means detuning of controller to avoid valve hunting. Large control errors may also need special attention.

Mechanical faults are recognized by valve controller diagnostics, and the faults are communicated to the maintenance organization [3].

Auxiliary sensor faults

In addition to valve position, which is the controlled value, valve controllers typically have auxiliary sensors, which speeds up and improves position control. Auxiliary sensors are e.g. supply and actuator pressures, and temperature. In case of a failure in any of the auxiliary sensors, the controller switches to a position-feedback mode where control actions are based on valve position only.

Faults in position sensor

On a general level, a feedback control loop needs both a setpoint and a measurement. A fault in the controlled

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value (i.e. measurement fault) prevents us from utilizing feedback control. Instead, feedforward control must be used to ensure that the (unmeasured) controlled value responds to changes in the setpoint.

For a valve controller, if there is a fault in the position sensor, the only option is *feedforward* control of valve position.

An intuitive solution for the cascade control setup in Figure 2, where the dotted line indicates a faulty or missing position measurement, would be replace the "Position Control" block, with e.g. a look-up table that picks a setpoint for actuator pressure based on given position setpoint. In this case, the look-up table would act as a feedforward controller, and replaces the feedback controller, which cannot operate because of the missing measurement needed for feedback control.

Next, we will present an alternative solution. We will replace the missing position measurement with a soft-sensor and continue with the same feedback controller as before [4]. The advantage of this solution is that there is no need for a separate feedforward controller. Instead, the same feedback controller can be employed both for ordinary feedback control and for control during a fault in position measurement. All we need is a model and a valve position simulation engine, which generates a virtual valve position value during a valve position failure. A simple model, which is easy to simulate is utilized [5,6,7].

Valve and actuator model

Consider a single acting, spring/piston actuator connected to a valve (Figure 3). The actuator consists of a spring pushing in one direction, and air pushing in the opposite direction. When air flows into/out of actuator, actuator pressure changes, and valve moves.

Compressed air in the actuator initiates a force that is proportional to air pressure. According to Hook's Law, the spring force is proportional to spring contraction [8] and considering pneumatic and spring forces (before considering friction) we notice that actuator travel (and valve opening) is proportional to actuator pressure. Introducing Coulomb friction, the net spring and pneumatic force must exceed the Coulomb friction threshold to ensure that the valve is moving.

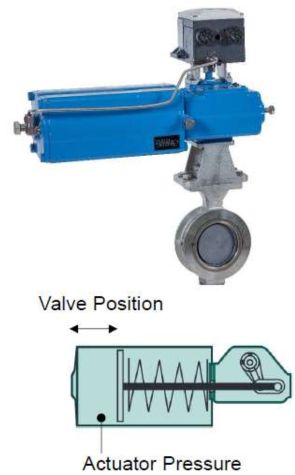

Figure 3. A valve package (above) and a detailed view of the single acting spring-return actuator (below).

A typical response of actuator movement to pressure changes is shown below (Figure 4) where we have plotted valve position vs. actuator pressure for an example actuator. Different colors indicate different movement directions. From this figure it is clearly seen that valve position is linear with respect to actuator pressure for each movement directions. However, because of friction forces, there is a clear gap between movement up and down curves (i.e. the Coulomb friction).

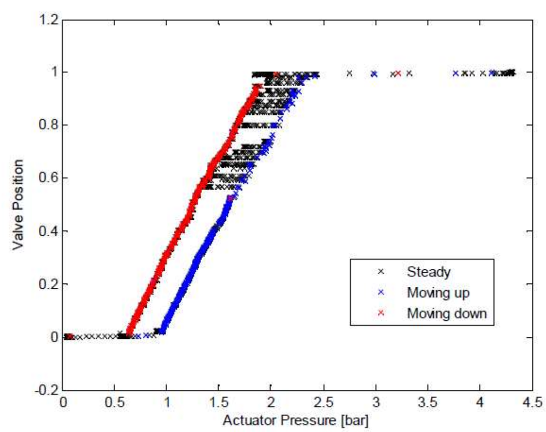

Figure 4. Valve position vs. actuator pressure for an example spring-return actuator.

Soft sensor

Above we observed a linear relationship between valve position and actuator pressure, when moving in one direction (up/down cases indicated by red/blue colors). Based on this finding we used the following equality for estimating new valve position h_e actuator pressure p_a

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$$h_e = \begin{cases} \min\left(1, max\left(0, \frac{p-p0-pf}{k_s}\right)\right) & if p > h_o k_s + p_0 + p_f \\ \min\left(1, max\left(0, \frac{p-p0+pf}{k_s}\right)\right) & if p < h_o k_s + p_0 - p_f \\ h_o & \text{otherwise} \end{cases}$$

(1)

where the parameters p_0 is the actuator pressure which equals spring pretension, p_f is net coulomb friction in pressure units, and k_s is spring constant (in pressure units / full stroke). The simulated position h_o is the only state variable needed for the simulation.

The parameters of Eq. 1 are identified during device calibration. Device calibration includes an automatic tuning sequence. This tuning sequence moves valve in both directions, which enables identification of the three parameters p_0, p_f, and k_s of Eq. 1. Note that for valve opening values other than extreme values (fully open/close), Eq. 1 is linear in the parameters.

The valve controller can switch to missing-valve-position-measurement mode automatically if it recognizes problems in position measurement. Alternatively, we can manually switch to fault-tolerant mode.

5 Results

We tested the suggested fault-control strategy by running a control valve in the laboratory. During the test we used a manual mode selector to switch between normal control and fault-tolerant mode with real position measurement replaced by soft-sensor value.

To demonstrate the robustness of the suggested method, we selected a high-friction valve for testing. For the test valve, the pressure change needed for valve reversal is 0.6 bar (i.e. pressure to compensate for friction), which can be compared to pressure change of 1.0 bar needed to compensate for spring forces during entire moving range (close to open). With such a large friction values, it is difficult to position the valve, especially when running in fault-tolerant mode.

An example test run is shown below in Figure 5 where trends for ordinary control which uses valve position, and fault-tolerant mode are shown. We used a setpoint sequence consisting of a ramp, and some step changes. The colors indicate the two different experiments: blue lines for ordinary control (which utilizes position measurement) and green lines for fault-tolerant control mode (when position measurement was neglected by the controller but recorded for trend plotting purposes).

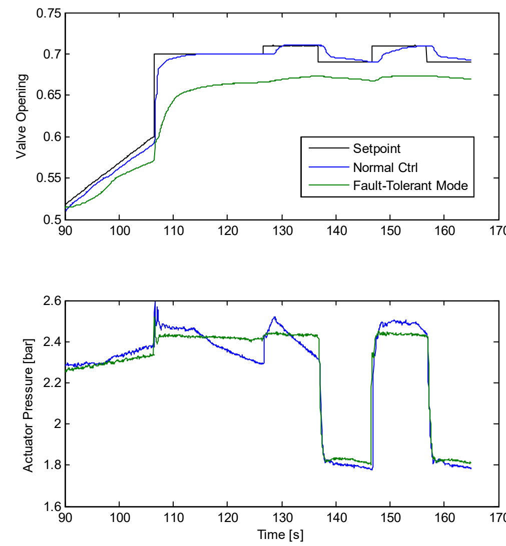

Figure 5. Comparison of control performance with normal control (blue) and with fault-tolerant control (green), which does not utilize position measurement. Above valve opening and setpoint, below actuator pressure.

6 Summary

We have developed a method for keeping a valve under control despite of loss of valve position measurement. Our solution is to replace the missing position measurement with a virtual measurement obtained from real-time simulations of valve. The same controller is used in both modes: closed-loop control (with position measurement from real sensor), and fault-tolerant control mode (with virtual measurement used for control).

Our test results from running a high-friction valve in laboratory suggest that valve control based on a virtual measurement works very well. The results demonstrate that the control accuracy suffers a little bit, as the control error increases with a few percentage points when operating the valve in position sensor-fault mode.

Because of the missing position sensor, it is impossible to for the valve the valve to follow its setpoint exactly. This is not a serious problem for valves operated by a PID control loop, because valve position errors are compensated by the PID controller. Control loops operated in manual mode, on the other hand, are expected to have a steady-state deviation in valve position.

The advantages with the suggested feature is that we can avoid an unplanned shut-downs of plant. This is expected to provide cost savings, added flexibility and more options for maintenance planning.

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